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Harmony and Technology Enhanced Learning

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1 Introduction

New technologies offer rich opportunities to support education in harmony. In this chapter we consider theoretical perspectives and underlying principles behind technologies for learning and teaching harmony. Such perspectives help in matching existing and future technologies to educational purposes, and to inspire the creative re-appropriation of technologies.

Some harmony curricula have long remained stable: others have undergone considerable change. Parncutt (1999) summarises a traditional curriculum:

> "Modern undergraduate harmony courses investigate compositional processes and devices by analyzing masterworks and by writing according to stylistic or generic models, often with the possibility of free composition and improvisation. Traditional harmonic theory involves the labeling of chords in tonal chord progressions and the composition of chord progressions in mainstream tonal styles. Students are trained to identify and classify the pitch materials of tonal music, and to apply stylistic conventions with the aim of reproducing mainstream tonal styles. Aural and visual experience with a range of materials develops students' intuitive understanding of harmony, even if they cannot necessarily articulate the underlying principles. An important spinoff of traditional harmony courses is that they improve students' general fluency in score reading and transcription."

Other curricula, particularly those dealing with popular music, can vary widely. In part, this diversity is due to different styles, ranging from jazz (Cork, 1996) to popular styles that mix tonal and modal resources (Pedlar, 2010). There are also different approaches to harmonic theory – for example Elliot's (2009) jazz harmonic theory and Tagg's (2014) theory of tonality in popular music. In response to such diversity, technology designers seek commonalities. As a unifying strategy, many designers take inspiration from theories of Music Psychology and related disciplines.

Few theories apply to all music. It can be hard to distinguish between universals of human perception and the effects of immersion in particular musical cultures (Parncut, 1999). Still, many theories of harmony offer rich insights. Relevant theories include those of Schenker (1906/1954), Lerdahl and Jackendoff (1985), Bregman (1984), Huron (2001), Riemann (Gollin and Rehding, 2011), Longuet-Higgins (1962, 1976), Balzano (1980) Deutch (1981) Krumhansl, (1990), Chew (2002), Tymoczko (2006) and others, for reasons examined in this chapter.

This chapter starts by reviewing representative theories of harmony, followed by representative educational technologies based on these theories. We will then consider educational technologies more generally, such as Computer Assisted Learning (CAI), Intelligent Tutoring systems (ITS), Rich Hypermedia, diverse specialised tools and networked systems, together with approaches related to embodied interaction.

Out of the various theories of harmony from psychology and related disciplines, *spatial theories of harmony* have been found particularly fruitful for embedding in technologies to embody and communicate insights about harmony
There are at least three reasons for this. Firstly, evidence from musicology, music psychology and cognitive science suggests that harmonic relationships are intrinsically spatial in nature (as explored in this chapter). Secondly, in situations where different styles and theories employ different terminologies, representations based on established spatial theories can provide a common language for harmonic abstractions. Thirdly, the human visual system excels at identifying relationships in spatial patterns and making spatial inferences - often more readily than when the same information is presented verbally. Consequently we will start with spatial theories of harmony.

2 Spatial models of musical harmony

Historical spatial models of harmony

Spatial models of harmony with two or more dimensions have been known since at least the 18th Century. In what may be the earliest published example, Euler (1739) while discussing frequency ratios between notes in just intonation, laid out twelve pitches in a diagram (figure 1a) with perfect fifths on a slanting vertical axis and major thirds arranged horizontally. Weber in 1851 published a "table of the relationship of keys" laying out the major and minor keys in equal temperament (figure 1b). Similar models were advocated subsequently by music theorists including Schoenberg (1954) and Lerdahl (1988). A separate strand of music theory focused on modeling pitch or pitch class, rather than key: Oettingen (1866), and more famously Riemann (1915) employed a diagram (figure 1c) using a lattice of pitches with two axes representing perfect fifths and major thirds. Their diagram was loosely similar to figure 1a. Oettingen and Riemann used this diagram to chart relationships between triads. During this period, uses of such diagrams were restricted and fragmented (Cohn, 1998). To paraphrase Cohn, theorists in the nineteenth century who were interested in the table as a map of triadic motion were not interested in exploring it under equal temperament, and theorists comfortable with equal temperament were not interested its potential to map triadic motion. However, it eventually became clear that the objects in Weber's table (which can represent keys or chords) matched those in Riemann's diagram: each triad may be represented by a point at the geometric centre of the pitch classes it comprises. The most widely used present-day versions use an equal tempered arrangement of pitch classes. This and similar diagrams are known as Tonnetz ('Tone network' in German).

Twentieth Century spatial models of harmony

Longuet-Higgins

Steedman (1972) argues that Longuet-Higgins (1962) was the first to show how a single diagram of this kind could be used to comprehensively analyse and explain nearly all harmonic entities and relationships: pitches, pitch classes, intervals, note spelling, chords, keys, and modulation; thus filling gaps in earlier work by Weber, Schoenberg, Helmholtz and Ellis. Taking just intonation
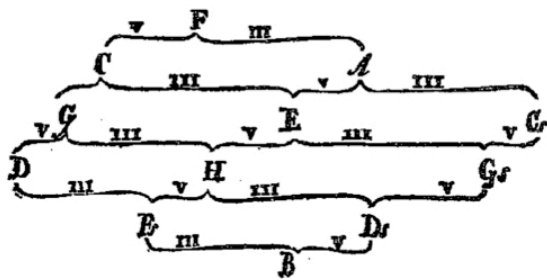
Figure 1a. A version of the Tonnetz from Euler's 1739 book "Tentamen Novae.

f	F	d	D	b	B	g#
bb	Bb	g	G	e	E	c#
eb	Eb	c	C	a	A	f#
ab	Ab	f	F	d	D	b
db	Db	bb	Bb	g	G	e

Figure 1b. Weber's chart of the relationships of keys (1851). Capital letters represent major keys; lowercase letters represent minor keys.
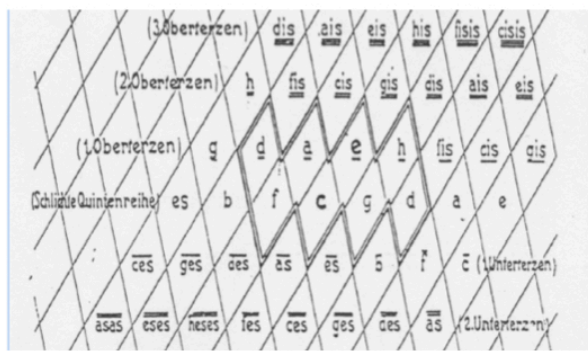

Figure 1c. Hugo Riemann version of Tonnetz using parallelogrammatic lattice with two axes representing perfect fifths, and major thirds From Riemann (1914-1915)
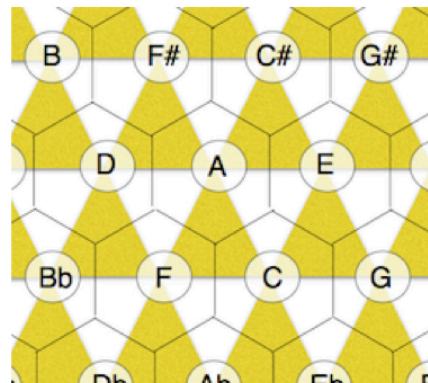

Figure 1d
Nodes in the hexagonal lattice are notes. Shaded areas in the triangular lattice are major triads. Unshaded areas in the triangular lattice are minor triads.

as the conceptual basis for harmony, Longuet-Higgins (1962) arranged pitches in an infinite array using three orthogonal axes representing the octave, the perfect fifth and major third. Longuet-Higgins together with Steedman (1972) demonstrated that this model could be used as the basis for computational models to carry out analytical tasks in harmony and to mirror aspects of human musical behavior. Ignoring the octave axis yields pitch classes rather than pitches, in which case the layout matches the standard Tonnetz.

Neo-Riemannian theory

Neo-Riemannian theory originated in the 20th Century to deal with problems in the harmonic analysis of late 19th Century chromatic music associated with Wagner, Liszt and Bruckner (Cohn, 1998). This music is generally triadic, but highly chromatic and organised around fluid and rapidly changing tonal centres. The theory, originating from Lewin (1982) analyses movement from triad to triad, according to a small repertoire of transformations such as motion to a parallel major/minor, motion to a relative major/minor, and what is known as 'leading tone exchange' (e.g. the transition between the chords C major and E minor). Hyer (1989) showed how such analyses could be graphed on an equal tempered Tonnetz. Different directions of motion on the graph correspond to different kinds of voice leading and the preservation of common tones.

Balzano's theory

A frequency-agnostic spatial model
Balzano's (1980) theory has an entirely different foundation to all of the above. It focuses on equal temperament, but applies to any tuning with 12 notes to the octave, including Blackwoods (1985) "range of recognisable diatonic tunings" and irregular tunings. Starting with *no assumptions* other than twelve objects with a circular ordering (twelve chromatic pitch classes being an example) Balzano uses elementary group theory to demonstrate that there exist exactly three well-defined co-ordinate systems. Two of these are familiar (the circle of semitones and the circle of fifths – both self-sufficient one-dimensional co-ordinate systems). The third co-ordinate system is two-dimensional, and has axes of major thirds and minor thirds. Both one-dimensional axes emerge as embedded diagonals in the two dimensional space. Balzano proved that there are no other well-defined co-ordinate systems. This co-ordinate space is a torus, but for practical purposes the 3x4 grid is laid flat and the pattern replicated like wallpaper, to reveal emergent patterns. Balzano demonstrated that this map accounts for a wide range of harmonic phenomena spanning scale formation, chord formation, keys, modes, and modulation. The resulting diagram is isomorphic to the Tonnetz, but emerges from consideration of properties entirely independent of frequency ratios. This gives useful alternative perspectives on the emerging structures. To convert the map to a map of *pitches,* as opposed to pitch classes, an octave axis may be added orthogonally.

3 Spatial models of harmony from psychology

Theory is well and good, but empirical studies in music psychology have independently led to spatial models of harmony. Work in this area has been carried out by Shepard, Deutsch and Feroe (1991) Krumhansl (1990, 1998) and

others. In a typical experiment, a musical passage, scale, chord or cadence is first played to establish a tonal context. A probe tone or chord then follows. Listeners are asked to rate the "fit", "stability" or "appropriateness" of the probe in light of the preceding musical context. Krumhansl used such work to generate a spatial map of distances between keys, found to agree fairly well with Weber's map. Krumhansl also studied how *chords* relate in a given key. The results could be represented by a two dimensional map similar to, though different in detail from the Tonnetz. Firm conclusions from these experiments are subject to limitations of lab-based studies: the results may not apply in musically realistic contexts. For this reason, spatial maps in educational applications often stress simplicity and clarity, rather than exact fidelity to potentially fallible psychological findings. Generally, though, empirical evidence supports the psychological reality of spatial harmonic maps of the kinds outlined above.

4 Relationships between the spatial models and their variants

The spatial diagrams of Euler, Reimman's Tonnetz, Weber, Schoenberg, Balzano and Longuet-Higgins are, in a sense, different perspectives on a single spatial model. Indeed, the diagrams are isomorphic – they can be converted into each other using shear and scale operations. However, variants lend themselves to different musical purposes, and are often associated with different communities of theoretical and musical practice. Before considering different educational uses, it is useful to itemise some of the properties the variants have in common (some of these properties have exceptions at the edges of maps).

1. Each interval is represented *uniquely* by a direction and distance in the space, and each chord quality has a *unique* shape and orientation in the space, regardless of key or transposition. This property is known as '*transpositional invariance*'.
2. Triads are represented by maximally compact 3-note shapes.
3. Dyads, seventh and ninth chords, and diatonic key regions, are represented by compact shapes.
4. Moves up or down by a perfect fifth, major or minor third (i.e. closely harmonically related intervals) are moves between *adjacent points* for notes, chords and keys (Figures 1c, 1d, 2b and 2d).

Properties 1-4 will be referred to as '*harmonic clarity*'.

5 Principled interactive systems using spatial maps of harmony

Interactive technological systems that use 2-D spatial maps can be grouped into two broad categories. The first category is *exploratory* or *discovery* systems aimed primarily at analysis, education, compositional sketching, exploration, and gaining insights into harmony. The second category is *instruments* – designed primarily for performance and improvisation*.* Instruments are mostly outside our scope, as they generally use spatial mappings optimised for performance, not for harmonic clarity. However, some instruments can be configured to use maps with harmonic clarity, bringing them into our ambit. Below we briefly consider a representative, rather than comprehensive, selection of educational uses of

interactive systems using spatial maps of harmony. All of the systems in this section have transpositional invariance and harmonic clarity.

Early history

Historically, many 2D keyboard instruments were constructed to facilitate playing in non-standard tunings (Keislar, 1987). Such instruments nearly always used layouts optimised for performance rather than harmonic clarity. An interesting partial exception, discussed by Helmholtz (1863/1954) is the Just English Concertina. A shift in emphasis came with the advent of computers. The first interactive applications on computers to use spatial models of harmony appear to have been the independently developed Harmony Space (Holland 1986, 1987, 1989) and Levitt's (Joffe and Levitt, 1986; Levitt, 1992) Harmony Grid. Below we review three broadly representative present-day such systems and their uses.

Isochords: live animation of playback of harmony

Isochords (Bergstrom et al, 2007) is a research tool for visualising harmonic structure in real time. It allows recorded MIDI encoded music to be animated. Isochords uses an equal tempered Tonnetz triangular layout with graph generators of perfect fifth and major third, with each note appearing as a circle. Considered as a two-dimensional interface, it displays pitch classes, but taking into account the graphic "two and a half-D" convention explained below, it distinguishes pitches. The unit cell Tonnetz pitch class pattern is replicated in the plane of the screen but mapped to a single octave. Isochords uses the size of individual circles to indicate octave height, with larger circles indicating deeper pitches. With this mapping, chords always have the same 2D geometrical shape regardless of inversion: 2D chord shapes are 'isomorphic up to inversion'. This feature helps beginners to recognise and name inversions. Isochords highlights the consonant intervals in chords by showing connecting lines. When a chord is displayed in Isochords, it is displayed simultaneously in all relevant locations in the plane.

Musix: Flexible multi-touch performance

Musix (Brett and Gerhand, 2013) is a production quality, commercially available multi-touch-based playable app for IOS. Musix is a musical instrument well-suited to improvisation, but given its configurability, it can also be used for compositional sketching and gaining insights about harmony. The representation focuses on pitch rather than pitch class. Musix assumes a 12-fold division of the octave and equal temperament. The spatial model of pitch is two-dimensional: Musix allows several different layouts. The lattice can be hexagonal or square. Hexagonal has advantages for performance uses, as the densest possible lattice arrangement of circular buttons is hexagonal, helping to minimise finger stretch. Special cases of layouts for Musix include "Harmonic Table" (essentially Balzano's version of the Tonnetz) - which has harmonic clarity, and Wicki-Hayd (Figure 2a), which balances melodic and harmonic movement. Due to multitouch operation, one finger typically plays one note, but
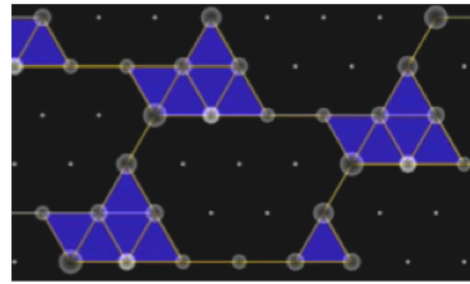
Figure 2a. Hayden-Wiki layout on Musix.

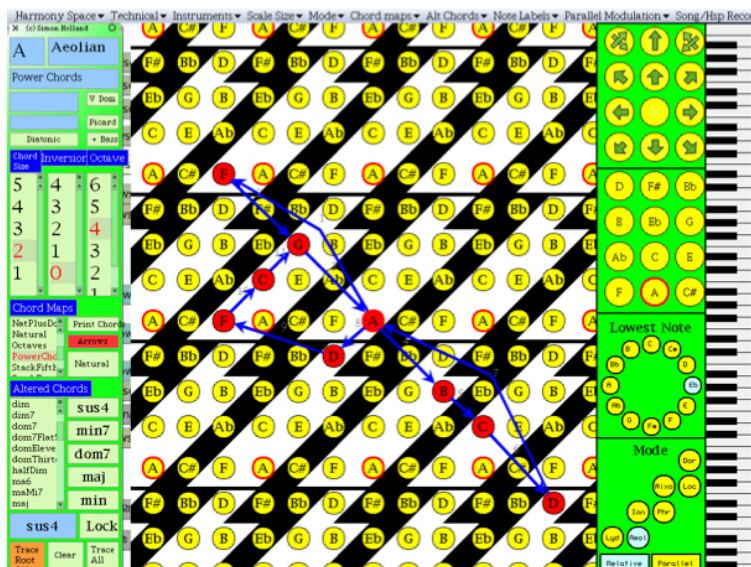Figure 2b. A triadic chord progression seen in Isochords.

Figure 2c Automatic trace in Harmony Space of a performance of Bowie's 'Suffragette City'. This trace is set to show the roots of the power chords used in the piece. The geometry of the trace, using a principle of 'maximal parsimony', suggests that this performance was in A Aeolian, with a mixolydian G cadence leading back to the Aeolian.

in the hex layout, by touching between notes, it is possible to play two or three note chords with a single finger.

Harmony Space: visualising analysing and manipulating harmony

Harmony Space (figure 2c) is designed primarily for analysis, education, visualisation and gaining insight about harmony, but it can also be played live (Howard et al, 1994; Bouwer et al, 2013). Harmony Space can be controlled by a single player, or by collaborative players using strategies outlined below.

Note circles are laid out in equal tempered major thirds and minor thirds, following Balzano's layout of the Tonnetz. The 3x4 array of twelve notes is replicated like wallpaper in a single octave (figure 2c). The layout allows eight different intervals to be represented by single steps in the eight compass directions without crossing other note-circles. This permits tracing of root and key movement in fifths, fourths, major third, minor thirds, and semitones up and down. This is useful for harmonic analysis in genres using extended harmony, such as Jazz, and in popular music with interplay of tonal and modal harmonic movement.

The dominant hand (or first player) sounds notes by highlighting circles. Mouse buttons control octave height (lower octaves appear darker). Single clicks may sound notes or chords of any size (dyads, triads, sevenths, ninths, etc.). Chord size, quality, inversion and voicing are dynamically determined with reference to current key and mode, as described below.

A moveable transparent virtual layer (the "key window") highlights the diatonic notes of the current key (figure 2c). The second hand (or other collaborative players) can move this layer, controlling modulation. The location and shape of the key window can be used to constrain thirds stacking, and thus, where desired, determine the default quality of chords with diatonic roots.

The second hand (or other collaborative players) may dynamically control chord size, or chord inversion, or mandate specific qualities. When playing collaboratively, root movement, modulation, altered chords and inversion may be assigned to different players (for example via optional dance mats).

This facilitates a game, teachable to novices, whereby any performance of a given chord sequence that follows a 'least action' rule will correspond to a functional harmonic analysis (figure 2c). This works because identification of chord functions, key, mode and modulations permit a chord sequence to be specified with the least number of actions (minimising explicitly-mandated chord qualities).

 Standard or user-defined "chord maps" may be used to associate chord qualities with scale degrees. Chord maps reflect mode- or genre-specific harmonic practices and voicings. As with Isochords, chord shapes are isomorphic up to inversion. Root movement, modulation and changes of mode may be graphically traced: non-default chords qualities are automatically annotated.

The above facilities are well suited to tracing, understanding, and playing Jazz chord sequences or modal modulations in popular music (Pedler, 2010; Tagg 2014): Lego Jazz Harmony analyses (Cork, 1996; Elliott, 2009) can be made accessible even to beginners. Harmony Space is not well suited for melodic playing and limited for studying voice leading. It is an example of a freely available research system, rather than a production-quality system.

Related interactive systems

Other applications using spatial maps of harmony include PaperTonnetz (Garcia et al, 2013) and HarmonyGrid (Adeney, 2011). PaperTonnetz is a research tool system that uses digital pens and interactive paper with pre-printed Tonnetz patterns for analyzing and creating chord progressions. HarmonyGrid (Adeney, 2011) is a computer-based interactive performance system developed to provide a generative music-making system intended to accompany, or play along with, improvising musicians. Related systems are due to Pachet (1994) Masaligin, 2003, Tornil and Baptiste-Jessel (2005) Adeney (2011) and Hedges and McPherson (2013).

If desired, alternative diatonic tunings can be explored with systems such as Musix and Harmony Space via external dynamic tuning synthesizers such as The Viking (Milne and Prechtl. 2008).

Commercially available physical 2D MIDI keyboards with configurable intervals steps on both axes can become 2D instruments with harmonic clarity by connecting them to MIDI modules. Velocity sensitive 2D keyboards with hexagonally arranged keys include the Axis (Axis, 2015) and Thummer (Milne and Pretchl, 2008), both now defunct. Similar systems are available, or planned, by Opal, Terpstra and Linn. The square-gridded Novation Launchpad, while not velocity-sensitive, could be adapted to control systems such as Isochord or Harmony Space.

Spatial theories of harmony offer deeply rooted principles from musicology and music psychology that can be exploited by designers of technologies to embody and communicate insights about harmony. However, there are numerous other approaches, particularly ones that draw on generally applicable frameworks for educational technology, as considered in the next few sections. These approaches, like all of those in this chapter are not generally substitutes for teachers, but can play useful complementary roles, provoking dialogue with teachers and peers, and promoting engagement with various musical materials.

6 General approaches to technology-enhanced learning for harmony

Computer Aided Instruction

Early work in computer-based music education (Computer Aided Instruction or CAI), involved presenting prepared materials in pre-planned branching paths, navigated according to student responses. CAI's relevance to harmony is limited to related areas that afford clear-cut questions and answers, such as aural training and simple multiple-choice topics. This limits the scope for developing

harmonic skills. However, current aural training software (proprietary, free or web-based) use rich aural contexts and expressive forms of input and output to enhance the value of these approaches. Audio samples permit exercises to be situated in musically realistic contexts, and midi instruments, customized software (Manzo, 2012) or pitch recognition technology can be used to deepen student engagement in various simple harmonic tasks. More generally, while CAI is limited, it can be useful in combination with some of the approaches explored below.

Intelligent Tutoring Systems for harmony

Intelligent Tutoring Systems (ITS) apply artificial intelligence (AI) techniques to teaching. The minimum requirement for an Intelligent Tutoring System is to be able to perform, or at least critique the task to be taught. Harmony has the advantage that for some harmonisation tasks, simple rules have long been codified - for example, four-part chorale harmonisation and voice leading rules. However, one effect of building ITSs for harmony (Thomas, 1985; Newcomb, 1985; Holland and Elsom-Cook, 1990; Brandeo et al, 1999; Holland, 2000; Caminha et al, 2000; Phon-Amnuaisuk and Siong, 2007) has been to demonstrate the limitations of received rules. Rule following was shown to be no guarantee of adequate harmonisations, and critiques based solely on the rules were often misleading or difficult to engage with. Still, Thomas was able to use Vivace, her system for teaching four-part chorale harmonization, as an experimental lab both to improve computational models and to inspire improved educational texts. This ultimately led to a commercial program, MacVoice, used at university level, which critiqued student voice leading. Related systems included Lasso (Newcomb, 1985) for two-voice 16th Century counterpoint, and systems by Caminha et al (2000) and Phon-Amnuaisuk and Siong (2007). Generally, standalone intelligent tutoring systems for harmony have not been widely adopted. The problem is that effective education in harmonisation requires more than just rules: awareness is needed of other things, such as high level phrase structure, a sense for when rules should be broken, and experience of manipulating harmony from diverse perspectives. Despite this, repositioning systems based on these principles as complementary tools rather than all-embracing tutors has had wider success, as explored below.

Current commercial harmonisation tools

Several current tools are effectively modern descendants of the above approaches. A good representative example is Harmony Builder. Harmony Builder (2015) is a commercial program for PC and Mac, that can assist in four-part harmonisation of melodies or bass lines, or developing chord progressions from scratch. The program 'knows' rules for harmonisation and voice leading. A key strategy of the design is to leave the user in control. Harmonisations are displayed in common music notation, but point-and-click tools enable working with minimal knowledge of music notation. The voice leading checker knows eleven different kinds of voicing leading error, but the user can switch these rules on or off in any combination, trying out alternatives rapidly and deciding aurally when to ignore rules. Harmonisation modules, generally without the tight focus on voice leading, exist as plugins to sequencers such as Sibelius, Finale and Cubase. Various other more or less standalone programs exist, such

as MusScore with the HarmonyRules plugin, and Harmony Assistant. The limitations outlined in the previous section still generally apply, but taken with a pinch of salt, and used to supplement engagement with peers and tutors, such tools can be helpful.

Rich Hypermedia

Pre-internet, Voyager's Beethoven's Ninth Symphony for the Macintosh (Martin, 2010) offered a seminal vision of rich musical hypermedia. This program included a performance of the symphony, playback controls, moment-by-moment commentary screens, aural and visual 'what-if' sidebars, historical material and much else. Earlier drafts of passages could be explored and critiqued. The system allowed educators to re-program and extend the system. A recent example of this approach (without the user-extensibility) is the Ninth Symphony App for IOS. Four highly rated Deutsche Grammophon recordings are included. Playback can be synchronised with the 1825 manuscript or a modern score (Dell'Antonio, 2013). Alternative performances can be switched seamlessly. Moment-by-moment commentary identifies harmonic developments. Graphics indicate which instruments are playing, and a ticker tape shows key changes. Systems of this kind command attention and motivate interest by surrounding a masterwork with a dense network of scholarly and analytical resources that can be explored at will. Such systems can be valuable resources to engage students and can be used in diverse ways to complement classroom teaching.

Networked and peer-to-peer systems

Networked systems represent an important area of rapid growth. They are likely to grow greatly in scope and integrate powerful aids, including elements of all of the above approaches, as we will now explore.
MOOCs are massively open online courses, delivered as distance education via the web, offering open access. Assessments may be machine- or peer-graded. MOOCs may be for-profit or not-for profit: courses are free or low cost. Completion rates are typically very low. Various harmony-related MOOC are currently offered, such as 'Fundamentals of Music Theory', 'Jazz Improvisation' and 'Write like Mozart ' by Coursera, and 'Developing your musicianship' from Berklee. Despite early claims, MOOCS have not generally been found effective for those outside of conventional educational systems. However, for a few highly committed students, typically with prior experience of the discipline required by conventional courses, they can provide effective supplementary material (Petre, 2013).
SoundCloud is a website allowing users to upload and share originally created audio files. SoundCloud allows comments to be posted at timed points in tracks. SoundCloud is primarily for musicians to promote their original music, but there are often peer-to-peer discussions on sound production, if not generally on harmony. However, the timed-comment feature suggests the potential for powerful educational uses in future networked systems. By themselves, networked services and sites have limited educational scope at present, but increasing integration with other technologies explored in this section is likely to

greatly enhance the role of such systems in advancing the study, analysis, and learning of harmony, as discussed at the end of this chapter.

Integration of diverse stand-alone tools

Diverse technological tools can enhance the learning of harmony in a variety of ways, particularly via integration with other technologies. We will touch on four such kinds of integration.

Firstly, intelligent tutoring systems, which tend to have limited value as standalone systems, could play supplementary roles in critiquing and teaching as part of large-scale, frequently updated online-based systems. Phon-Amnuaisuk and Siong (2007) have prototyped systems exploring these possibilities.

Secondly, on-line repositories and databases (for example containing encoded notation, digital audio or metadata) offer rich opportunities for accessing, studying, analyzing and comparing the harmony of individual pieces, or whole corpora (Downie et al 2010). At present, relatively rare technical skills are required to take advantage of these opportunities. However, music information retrieval tools are steadily becoming more accessible, exploiting techniques such query by singing (deHaas, 2012). By such means, rich existing public resources that currently require specialized skills to access could become as readily accessible as Wikipedia.

A third way in which the integration of currently standalone tools could transform education in harmony relates to tools for the harmonic analysis and manipulation of audio. Tools for polyphonic pitch recognition and manipulation such as Melodyne (2009) allow constituent lines from polyphonic audio files to be recognized, enabling notation to be generated from audio and individual notes to be manipulated. The integration of this kind of capacity with tools such as music notation systems, audio workstations, rich hypermedia, online repositories and networked teaching systems promises new kinds of flexibility, immediacy and engagement to tools for learners.

Fourthly, there are many programming languages for music: some, such as Symbolic Composer (2014) have rich facilities for manipulating harmonies, tonalities, chords, and intervals. These have a wide range of educational uses, for example, synthesizing variant examples to test analytical insights (a form of 'analysis by synthesis'). This generally requires programming expertise, but versions of these developed for non-experts and children (as pioneered by Music Logo – see below) could offer new ways to integrate and unlock all of the above resources for new educational applications.

New theories: implications of Embodied Music Cognition

Many of the approaches above are sedentary in conception, ignoring the deep link of music and harmony with physical movement. Physicality has often been exploited in music education in the past, for example by Dalcroze Eurhythmics and Curwen's Solfege hand signs. New theories from cognitive science and music psychology are combining with emerging technologies to create new educational opportunities.

Research in Embodied Cognition posits sensory-motor skills and physicality as the basis of all human cognition. Researchers such as Zbikowski (2005), Saslaw

(1996) Larson (1997), and Johnson and Larson (2013)) have applied embodied cognition to analyses of musical concepts, including the harmonic concepts of Schoenberg, Schenker and Riemann (Saslaw, 1996). Embodied Interaction (Dourish, 2004) applies similar ideas to the design of interactive technologies. Researchers such as Leman (2008), and Wilkie et al (2010) and Holland et al (2013) have combined these two strands to study and design embodied musical technologies, with Wilkie et al. (2010) and Holland et al, 2009, 2011) and Bouwer et al (2013) focusing particularly on harmony. Jeanne Bamberger's (1974, 1975) early music programming language Music Logo prefigured these ideas, emphasising physical metaphors for musical concepts. Holland (1990b) in collaboration with Desain and Honing had instrumental performers move around physically in a low-tech human-powered Tonnetz with their location controlling the harmony played by a live band. The language Harmony Talk was an experimental programming language (Holland, 1991) to drive virtual musical robots around in a 2D Tonnetz to create harmonic sequences. Hodge and McPherson (2013) built a 3D interaction system using hand-held controllers and a video tracking system to allow users to gesturally navigate a 3D Tonnetz. Adeney's (2011) HarmonyGrid is an immersive system that allows instrumental performers to create their own generative music accompaniment by moving around on a stage with a Tonnetz-like floor projection. A motion-tracked version of Harmony Space (Holland et al, 2009) allowed people to create live accompaniment to popular songs by navigating through a floor projection of Harmony Space. Systems of this kind tend to be well received by users, and there is evidence that working with spatial maps of harmony can help beginners to learn how to articulate and manipulate harmonic concepts (Holland et al 2013a). These approaches have the potential to break into the classroom as devices for tracking parts of the body accurately (potentially via phones and watches) become cheap and commonplace.

7. The Future

Combining some of the ideas explored above, we consider visions of future developments

Integrated Music Wikis and repositories: students interested in the harmony of any piece of music from the earliest tonal music to the present day should be able go to wiki-like sites to read, create or modify line-by-line annotations, commentary and analysis. Pieces from any genre or period that employ harmonic processes or devices in common could have crowd-sourced cross-links to each other and to scholarly discussions. Links should make it possible to hear pieces and to annotate or modify copies using a variety of representations and input mechanisms.

Tools for wide engagement: Interactive systems that use spatial maps of harmony can allow those with limited skills in reading music, singing or playing an instrument to manipulate and reflect articulately on the materials of harmony, as well as engaging fully with music wikis. The application of gamification (i.e. game-like) techniques is an obvious way to motivate beginners to engage with spatial representations of harmony.

Support of expert skills: Those learning fine-grained skills in the analysis of harmony and composition in mainstream tonal styles need sustained practice and expert feedback. Human teachers are essential here, but integrated combinations of well curated large online systems, peer-to-peer advice and intelligent tools could provide valuable complementary assistance.

Acknowledgments

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